What is Detachment?

Data Analysis Techniques to Understand and Control Detachment in Tokamaks

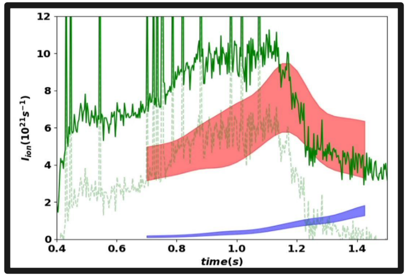
Daljeet Singh Gahle, IAEA

Sixth IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis
Fudan University, Shanghai, China
9-12th September 2025

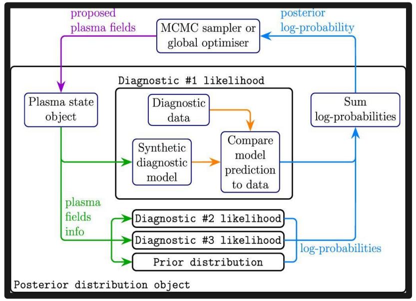
Contact on in

Executive Summary

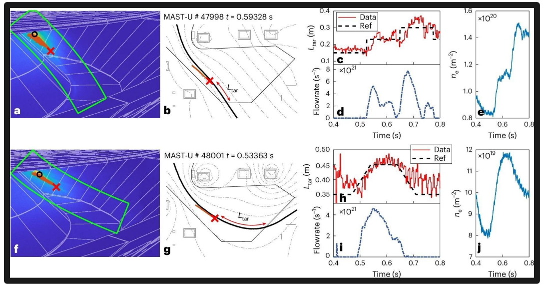
What is detachment?



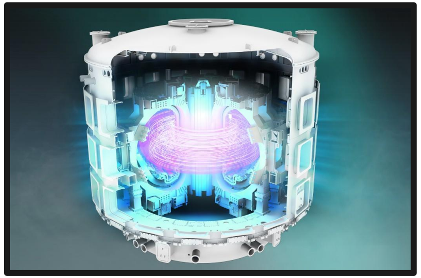
Analysing detachment



Controlling detachment



Conclusions and Recommendations



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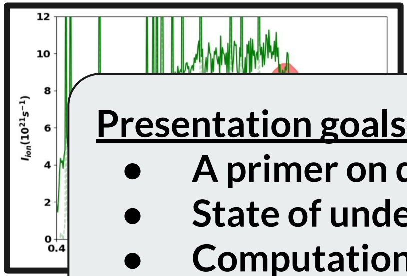

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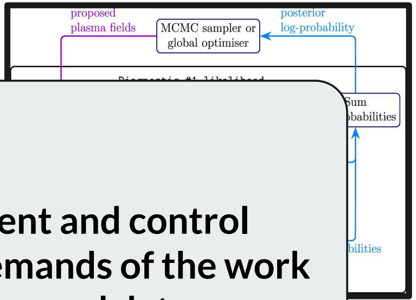
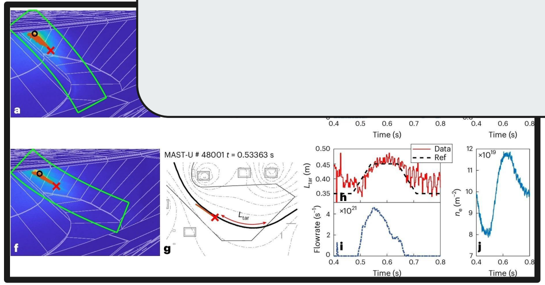


<u>Presentation goals:</u>

- **A primer on detachment**
- **State of understanding detachment and control**
- **Computational and statistical demands of the work**
- **Advocate for advances in software and data practices**

Controlling det



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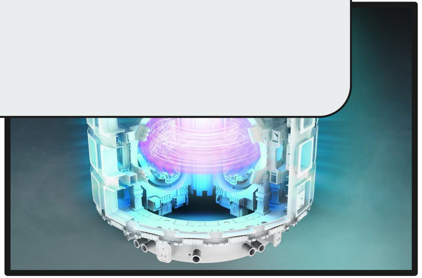

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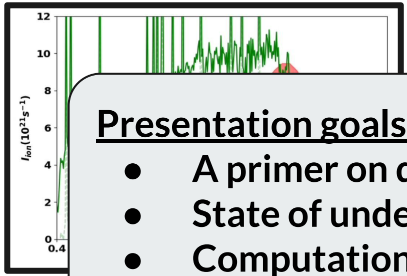

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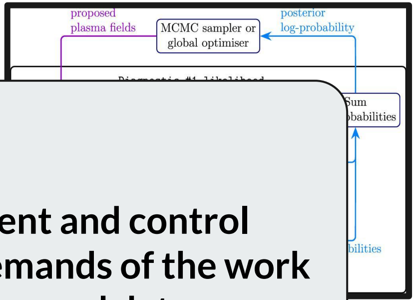

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Not comprehensive tech' review (see ass. conf. Paper)

Controlling det

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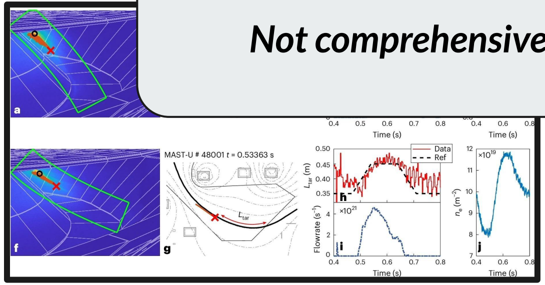
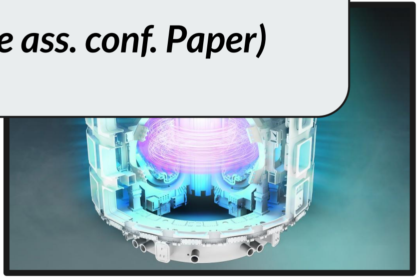
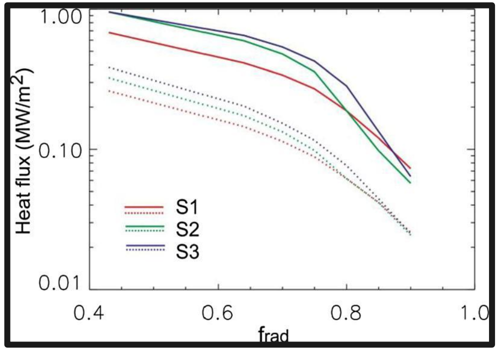




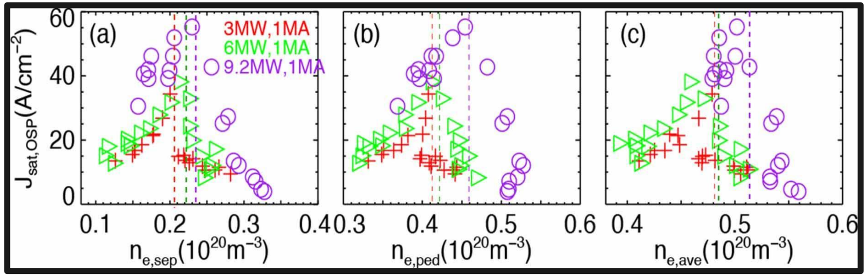
What is detachment?

"The method of taking a GW power source and getting a sub MW/m2 heat flux"

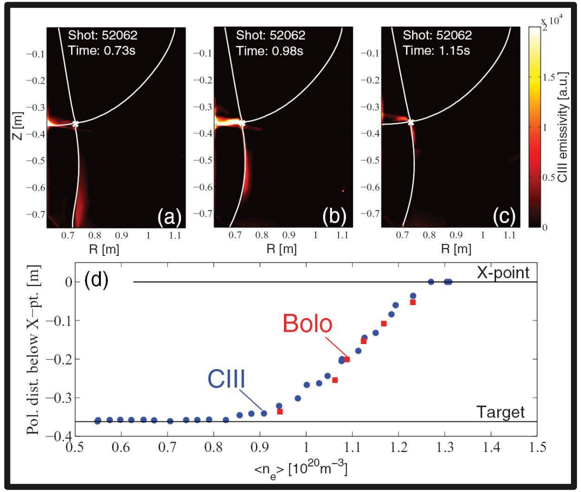
Some phenomenological examples for how detachment is observed:



Source: Y Feng *et al* 2021 *Nucl. Fusion* **61** 086012 (link)



Source: HQ Wang *et al* 2023 *Nucl. Fusion* **63** 046004 (link)



Source: C Theiler *et al* 2017 *Nucl. Fusion* **57** 072008 (link)

What is detachment? - Mathematical Models I

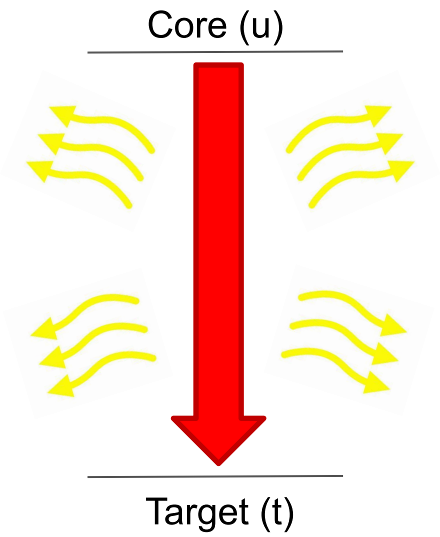
The overall dynamics of detachment can be understood from simplified 1D models.

2 Point Model (2PM):

$$n_t T_t = 2 n_u T_u$$

Parallel heat transport:

$$q_{\parallel}^{cond} = -\kappa_0 T^{5/2} \frac{dT}{dl}$$



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$$n_t T_t = 2 n_u T_u (1 - f_{mom})$$

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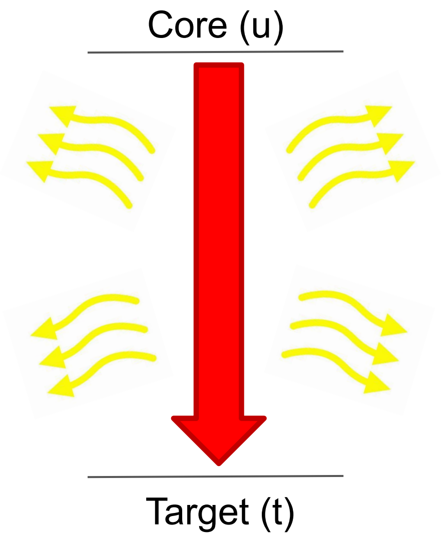


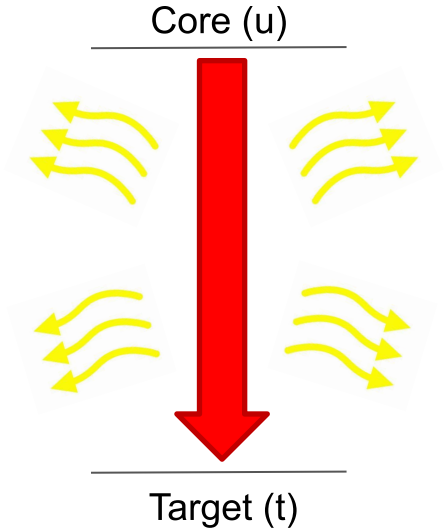
What is detachment? - Mathematical Models I

Target conditions from the Modified 2-Point Model (M-2PM):

$$T_t(eV) \propto \left[\frac{q_u^{10/7}}{n_u^2 L^{4/7}}\right] \left[\frac{(1-f_{cool})^2}{(1-f_{mom})^2}\right] \left[\left(\frac{R_u}{R_t}\right)^2\right]$$

$$\Gamma_t(m^{-2}s^{-1}) \propto \left[\frac{n_u^2 L^{4/7}}{q_u^{3/7}}\right] \left[\frac{(1-f_{mom})^2}{(1-f_{cool})}\right] \left[\left(\frac{R_u}{R_t}\right)^2\right]$$

$$n_t(m^{-3}) \propto \underbrace{\left[\frac{n_u^3 L^{6/7}}{q_u^{8/7}}\right]}_{\text{Inputs}} \underbrace{\left[\frac{(1-f_{mom})^3}{(1-f_{cool})^2}\right]}_{\text{Losses}} \underbrace{\left[\left(\frac{R_u}{R_t}\right)^2\right]}_{\text{Shape}}$$



An expanded 2PM by including the integrated parallel head transport equations.

Constants known, but omitted for clarity.

Source: P C Stangeby 2018 *Plasma Phys. Control. Fusion* **60** 044022 (link)

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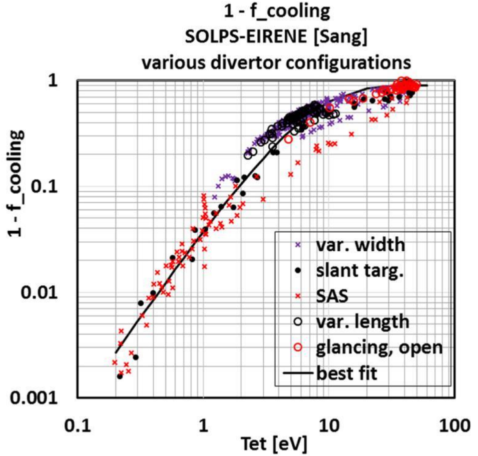

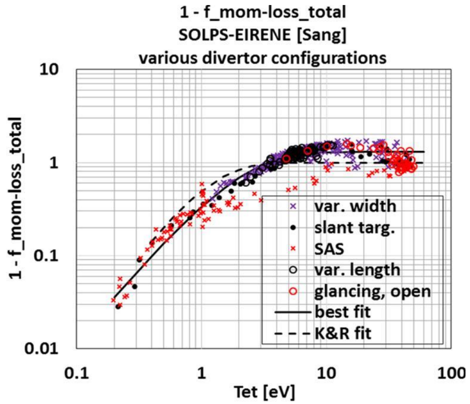

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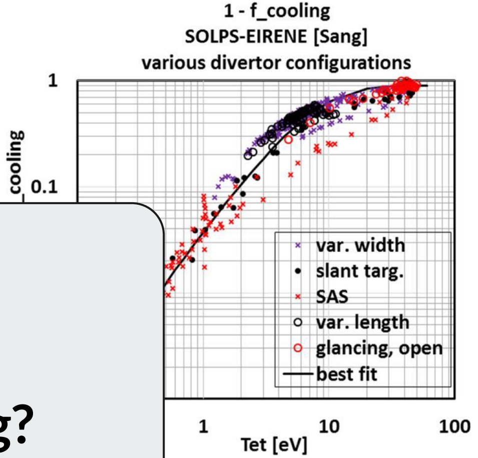
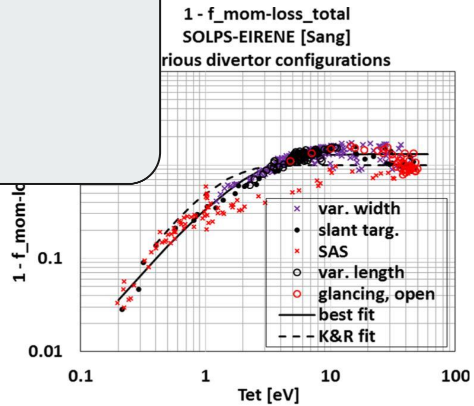
$\Gamma_t(m^{-2}s^{-1}$

$n_t(m^{-3}$

But what is actually happening?





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What is detachment? - Mathematical Models II

Power and Particle Balance derivation:

$$I_t = I_{ion} - I_{rec}$$

Power Balance:

$$P_t = P_{SOL} - P_{rad}^{A>1} - P_{ion}^{H} - P_{rec}^{H}$$

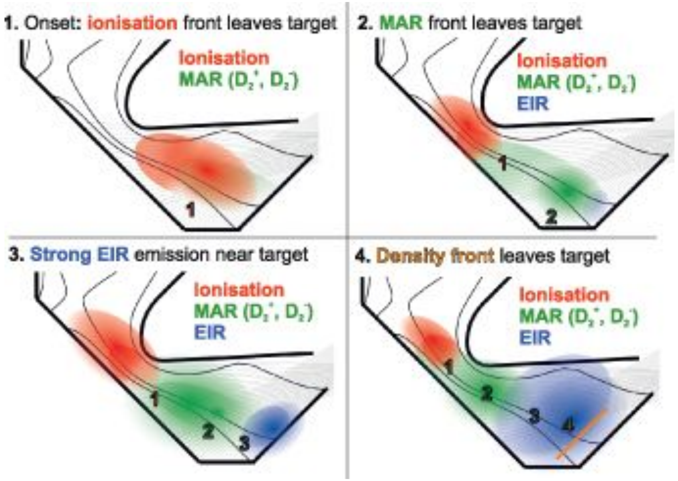
Power and Particle Balance:

$$I_t = \frac{P_{SOL} - P_{rad}^{A>1}}{E_{ion} + \gamma T_t}$$

Momentum Balance:

$$p_t \propto I_t \sqrt{T_t}$$

Sources: K. Verhaegh et al 2019 *Nucl. Fusion* **59** 126038 (link)



Sources: K. Verhaegh et al 2023 *Nucl. Fusion* **63** 016014 (link)

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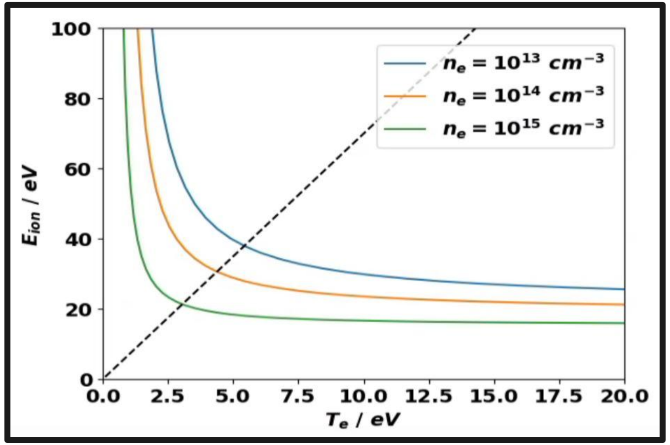

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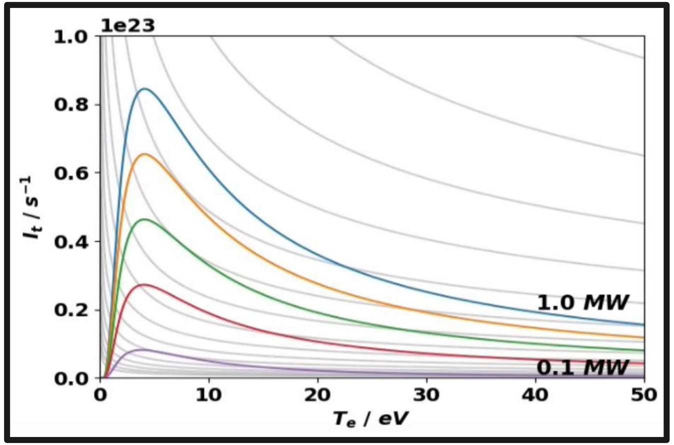
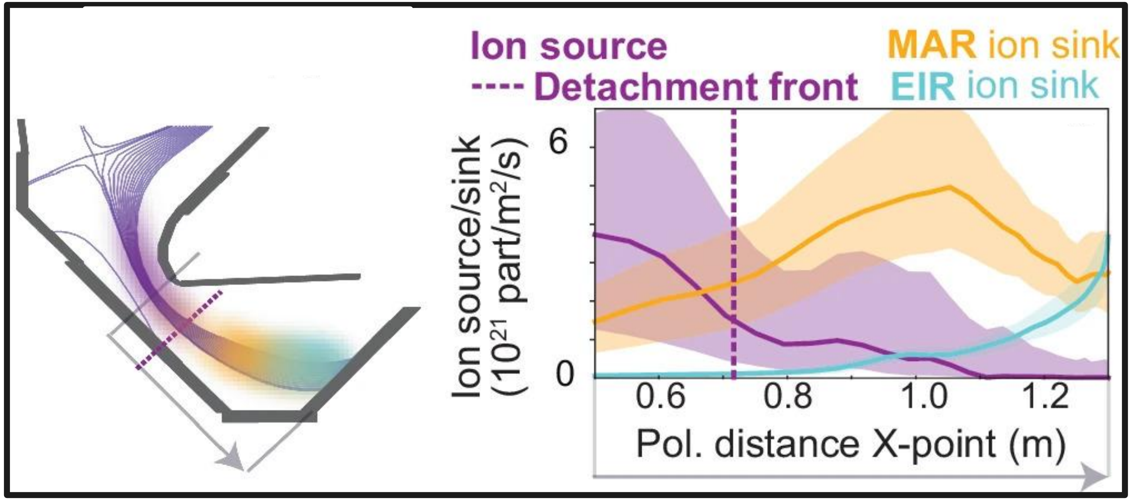


What is detachment? - This is Detachment!

$$D_\alpha = \boxed{n_e n_D PEC^{3\to2}_{exc}} + \boxed{n_e n_{D_2^+} PEC^{3\to2}_{mar}} + \boxed{n_e n_{D^+} PEC^{3\to2}_{rec}}$$



$$I_t = \int \boxed{n_e n_D SCD} - \boxed{n_e n_{D_2^+} MAR} - \boxed{n_e n_{D^+} ACD}\, dl$$

Source: K. Verhaegh *et al*, 2025, *Nature Comm. Phys.*, **8**, *215* (link)

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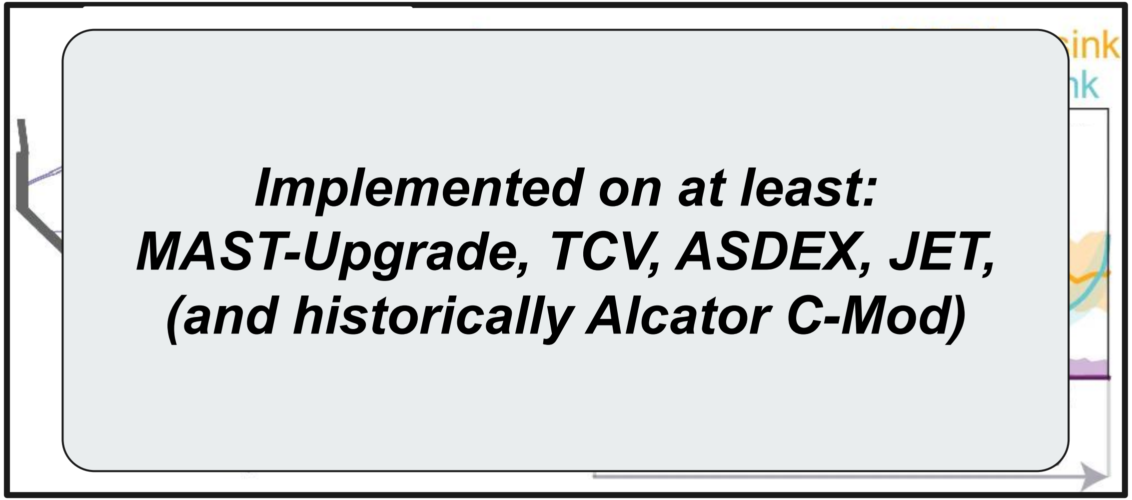

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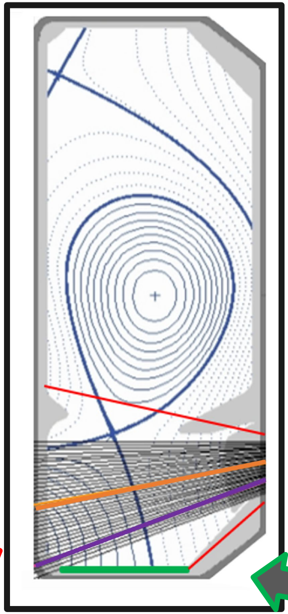
Source: K. Verhaegh *et al*, 2025, *Nature Comm. Phys.*, ***8***, *215* (link)

Diagnosing Detachment - Diagnostics

Bolometry:
$\int \Sigma_z P_z(L)\, dL$

Cameras:
ε , $R_{\delta/\varepsilon}$
f_{rec} , T_e , n_e , τ
c_z, n_e
I_{ion} , I_{rec} , I_{mol}



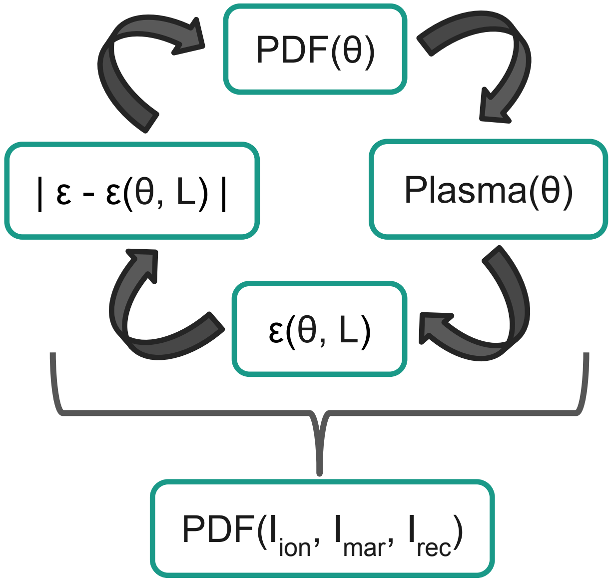
Spectroscopy:
$\int \varepsilon\, dL$, $R_{\delta/\varepsilon}$
f_{rec} , $\langle T_e \rangle$, $\langle n_e \rangle$, τ
$\langle c_z \rangle$, $\langle n_e \rangle$
I_{ion} , I_{rec} , I_{mol}

Langmuir Probes:
Γ_i, n_{et}, (T_{et}?)

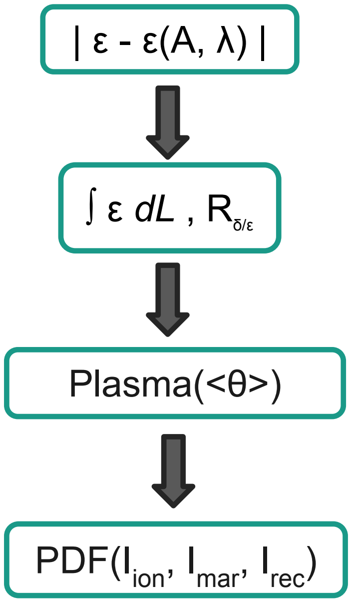
Diagnosing Detachment → Analysis Techniques

$$D_\alpha = n_e n_D PEC^{3\to2}_{exc} + n_e n_{D^+} PEC^{3\to2}_{rec} + \left(n_e n_{D_2^+} PEC^{3\to2}_{mar} \right)$$

Forward modelling (circular):



Inverse problem (linear):



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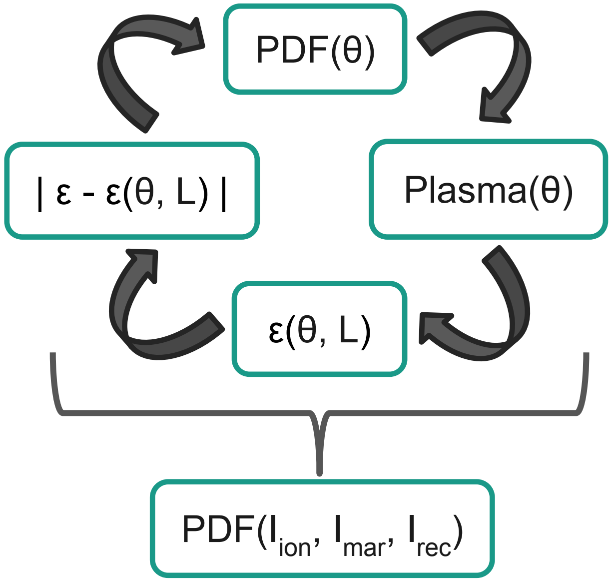

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Sources:

- C Bowman et al 2020 Plasma Phys. Control. Fusion 62 045014
- T Nishizawa et al 2020 Plasma Phys. Control. Fusion 62 085005
- A Perek et al 2022 Nucl. Fusion 62 096012
- F Federicci et al 2023 arXiv:2312.16356 [physics.plasm-ph]
- DD Greenhouse et al 2025 Plasma Phys. Control. Fusion 67 035006
- DS Gahle et al 2025 (to be submitted)

Diagnosing Detachment → Analysis Techniques

$$D_\alpha = n_e n_D PEC^{3\rightarrow2}_{exc} + n_e n_{D^+} PEC^{3\rightarrow2}_{rec} + \left(n_e n_{D_2^+} PEC^{3\rightarrow2}_{mar} \right)$$

Forward modelling (circular):

Sources:

- K Verhaegh et al 2019 Nucl. Fusion 59 126038
- B Lomanowski et al 2020 Plasma Phys. Control. Fusion 62 065006
- K Verhaegh et al 2021 Plasma Phys. Control. Fusion 63 035018

Inverse problem (linear):

| ε - ε(A, λ) |

↓

$\int$ ε *dL* , $R_{\delta/\varepsilon}$

↓

Plasma(<θ>)

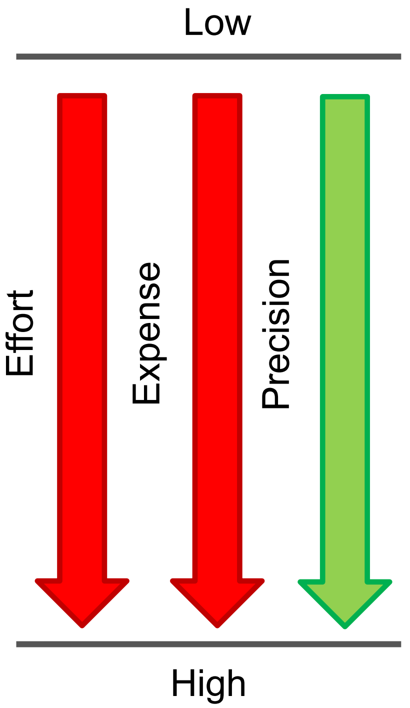
↓

PDF(I_{ion}, I_{mar}, I_{rec})

Diagnosing Detachment → Optimisation and Sampling

Style	Examples
Exact	• Least Squares Inversion (Unstable) • Grid evaluation
Random	• Monte Carlo
Pseudo-gradient	• Markov Chains (MCMC) • Principal Component Analysis (MCMC) • Affine-Invariant Ensemble Sampling • Evolutionary/swarm algorithms
Gradient	• Newtonian
Curvature	• Broyden–Fletcher–Goldfarb–Shanno (L-BFGS-B) • Hamiltonian Monte Carlo (HMC)

Diagnosing Detachment → Optimisation and Sampling



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Analysis Techniques - Comparative Analysis

	Physics Inferences			Diagnostics (Requirements)			Open Source		Notes	
Method	Atoms	Molecules	Impurities	Visible	UV	Other	Repo	Production	Machine Agnostics	Fwd/Inv
Verhaegh 2019	✅	❌	❌	✅	❌	❌	❌	❓	✅	Inv
Bowman 2020	✅	❌	❌	✅	❌	TS, LP	❌	❓ (MAST-Upgrade)	❌	Fwd
Lomanowski 2020	✅	❌	❌	✅	✅	❌	❌	❓	✅ **	Inv
Nishizawa 2020	✅	❌	❌	✅	❌	❌	❌	❓	✅	Fwd
Verhaegh 2021 (BaSPMI)	✅	✅	❌	✅	❌	❌	❌	❓	✅	Inv
Perek 2022	✅	❌	❌	✅	❌	❌	❌	❓	✅	Fwd
Federicci 2023	✅	✅	❌	✅	❌	TS	✅	❓ (Magnum PSI)	❌	Fwd
Greenhouse 2025 (D-MIBAS)	✅	✅	✅ (He I only)	✅	❌	TS, LP	❌	❓ (MAST-Upgrade)	❌	Fwd
Gahle 2025 (BaySAR)	✅	❌	✅	🌟	🌟	🌟	✅	❌	✅	Fwd

Detachment Control

For reactors, beyond understanding is the need to control detachment!

Two simple goals:

1. Maintain a detached divertor
2. Avoid disruptions

Detachment Control - Types of Control

For reactors, beyond understanding is the need to control detachment!

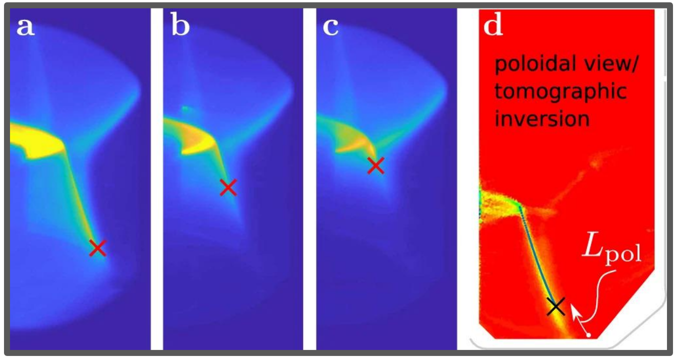
With three means:

Feedback (e.g. PID)	Feedforward	Predictive (e.g. MPC)
• **Principle:** Actuator evolves to minimised sensor signal from preprogrammed path	• **Principle:** Actuator evolves to prevent the sensor signal from crossing preprogrammed limits	• **Principle:** Actuator evolves to follow a predictive model to either ○ Path follow, or ○ Stay within limits
• **Key Feature:** Reactive	• **Key Feature:** Preemptive	• **Key Feature:** Proactive
• **Example:** Diverter Control	• **Example:** Line-average density (core)	• **Example:** Disruption mitigation

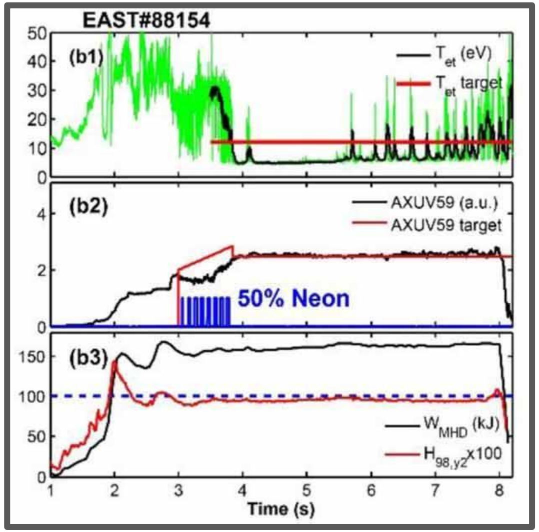
Detachment Control - In Practice

A range of detachment proxies have been used for real-time, **feedback** control!

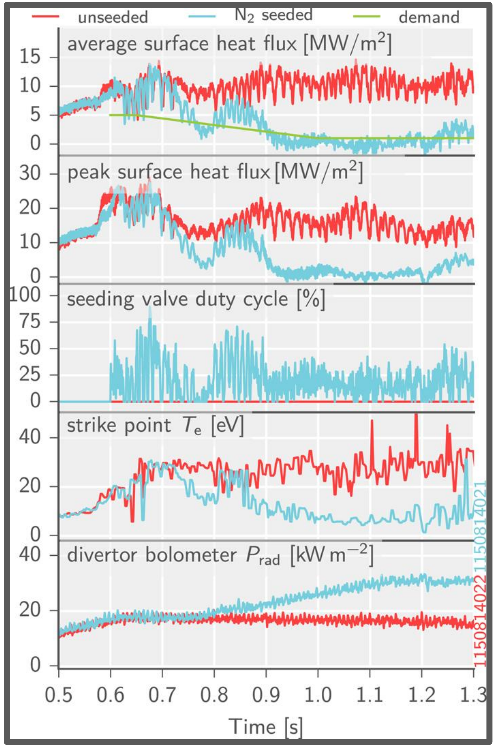
C III with D_2 on TCV [Ravensbergen et al 2021]



P_z with Ne/D_2 on EAST [Xu et al 2020]



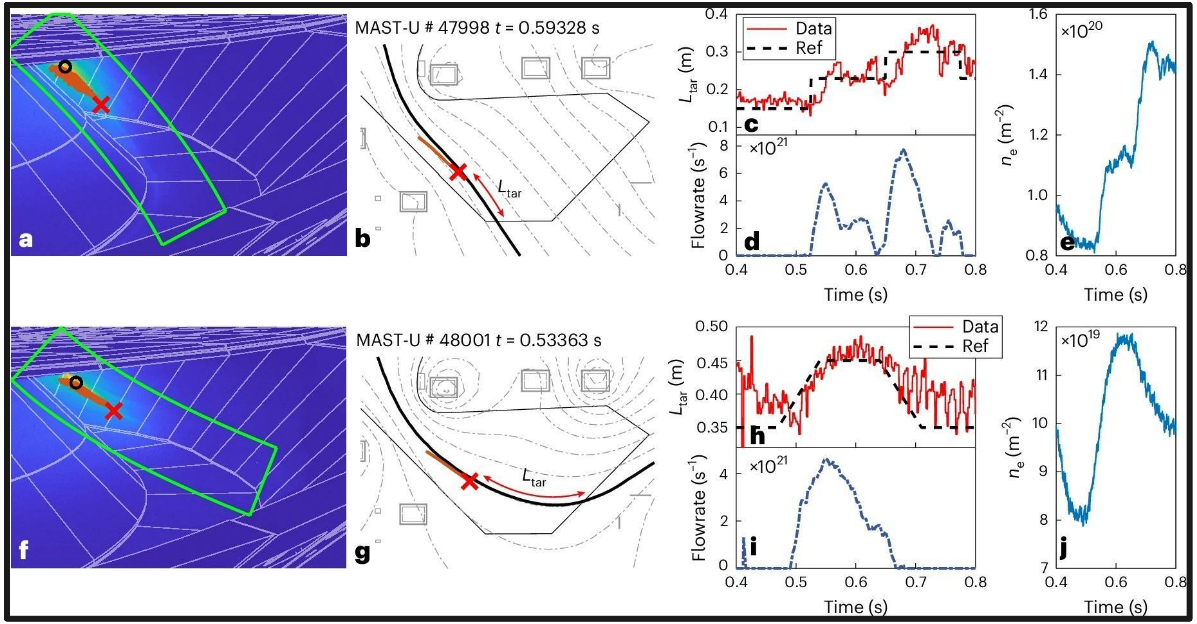
T_t with N_2 on
Alcator C-Mod [Brunner et al 2016]



A range of control signals:
C III, P_z, T_t, T_e, Γ_i, and I_t

Detachment Control – Breakthrough!

Real-time, feedback control of the detachment on MAST-Upgrade using Fulcher (D_2) emission:



Source: B. Kool *et al*, 2025, *Nat. Energy* (link)

Detachment Control – Breakthrough! Why?

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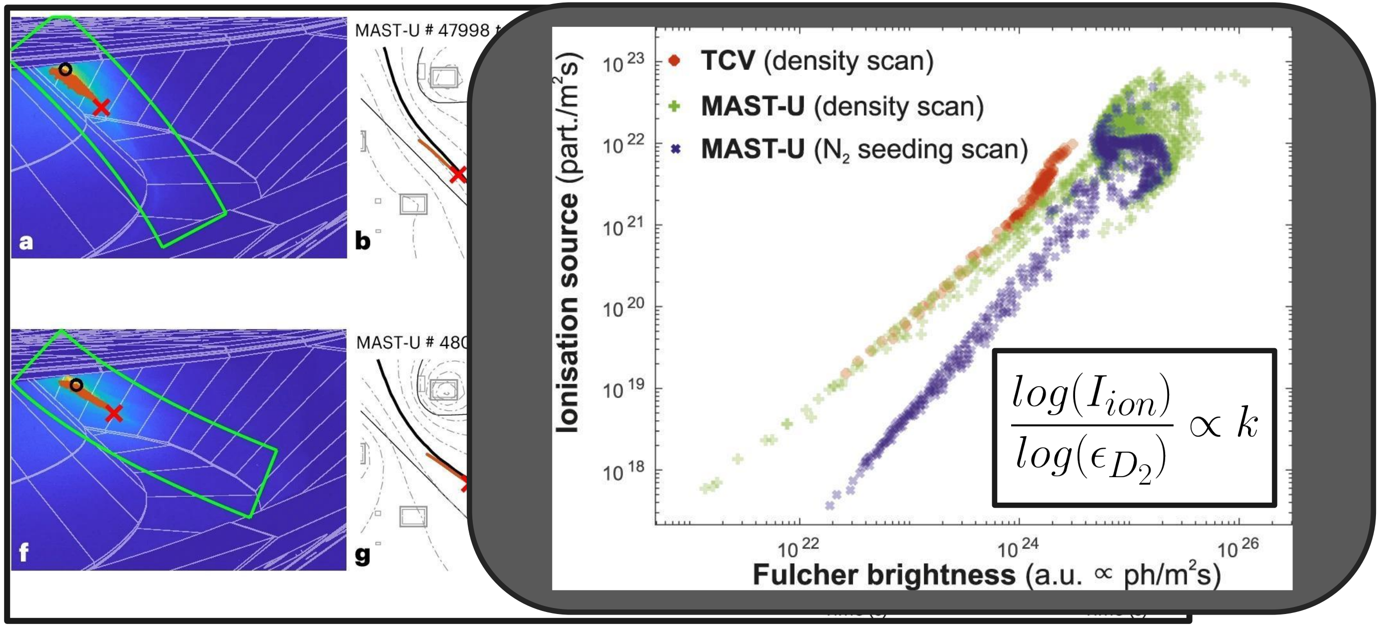

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K. Verhaegh *et al* 2023 *Nucl. Fusion* **63** 016014 (link)

Detachment Control - Application to Power Plants

Overall control must keep operation between the states of "attached" and "radiative collapse"!

High level suggestions:

- Fulcher emission tracking
- Photodiodes vs CCD cameras
- AI predictive control

Why AI predictive control?

- Plasma response << gas response

	Current	Reactors
Gas response (ms)	10-200	>>10
Detachment response (ms)	10-50	< 1
Compute time (ms)	< 1	?
Senor (Optics)	Cameras/Specto'	Minimal/None

What do we Need Next

These next steps are the motivation for this review talk!

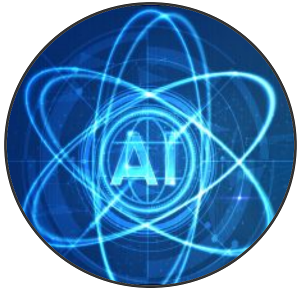
1. Productionise, automate, and open source analysis and control codes and results
2. Build large results databases
3. Big data and AI analysis for deeper and general insights

Goal: Move detachment from a physics to engineering problem!

Communities of Interest

Technical Meetings:

- Fusion Data Processing, Validation and Analysis
- Experience in Codes and Standards for Fusion Technologies



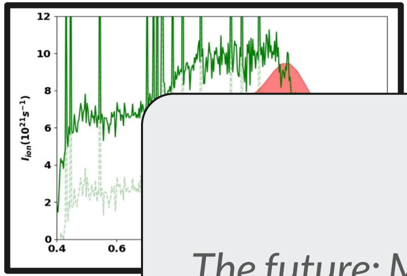
Coordinated Research Project: AI for Fusion and the Fusion Data Lake Project

Open Source Software for Fusion Energy (OSSFE) Conference

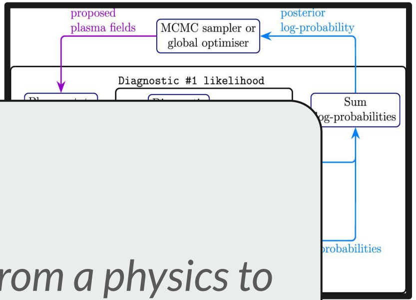
Munich Urban Colab
March 10th - 12th, 2026

Conclusion

What is detachment?



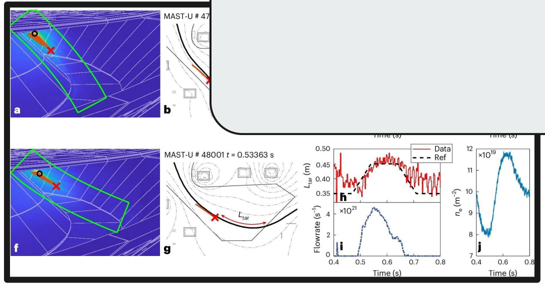
Analysing detachment

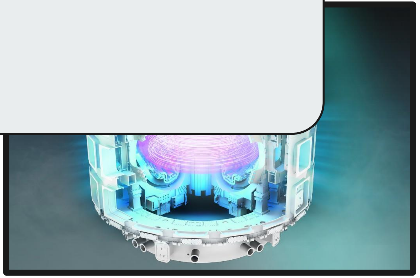


<u>The future:</u> Move detachment from a physics to engineering problem!

Controlling detachm

endations





What is Detachment?

Data Analysis Techniques to Understand and Control Detachment in Tokamaks

Daljeet Singh Gahle, IAEA

Sixth IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis
Fudan University, Shanghai, China
9-12th September 2025

Contact on in